

On the Ionisation of Various Gases by α -, β -, and γ -Rays.

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When an ionising agent traverses a gas, the ionisation between two parallel planes separated by a distance δx is measured by $K \cdot \delta x$, where K denotes the ionisation per cubic centimetre when it is ionised throughout by an intensity of the ionising agent equal to that between the planes. In order to obtain values of K in practice, the gases under investigation are reduced to such low pressures that they absorb only a small fraction of the energy of the ionising agent, and a set of readings with different gases then gives their respective values of K for the intensity of the ionising agent where it enters the ionisation chamber. A test that the absorption of energy in the gas is small is that the ionisation is directly proportional to the pressure. Strutt* has carried out a set of experiments on the ionisation of a number of gases by α -, β -, and γ -rays.

This paper gives the ionisation of a larger number of gases for these rays and the conclusions which may be deduced from the results of the experiments. Let us first consider the α -particle.

§ 1. The α -particle, as the experiments of Prof. Bragg and the writer have shown, is a better ioniser towards the end of its course than at the beginning. We must, therefore, compare the ionisations in different gases for the same velocity of the α -particle. If x is a distance along the course of an α -particle measured from where it enters a gas, and L is its complete range, then, if the ratio L/x is kept constant when dealing with a number of gases, the velocity of the α -particle is the same at the end of each distance x whatever the nature or pressure of the gas. This follows from the fact that since a slab of matter cuts the range of the α -particle down by very approximately the same amount in whatever part of the path it may be placed, the ratio of the range of an α -particle in one gas to that in another gas is independent of the initial velocity of the α -particle. Therefore, the distances in various gases at the end of which the α -particle has the same velocity are given by $(L-x)/L = \text{const.}$, that is $L/x = \text{const.}$ But the sets of relative ionisations, each of which is taken with a different velocity of the α -particle, will be different unless the ionisation along the course of an α -particle is

* 'Phil. Trans.,' A, vol. 196, p. 507, 1901, and 'Roy. Soc. Proc.,' p. 208, 1903.

similar in all gases, that is, unless the ratio of the ionisation at the distance x_1 to that at the distance x_2 in a gas, where $L/x_1 = K_1$, $L/x_2 = K_2$, and K_1 , K_2 , denote constants, is the same for all gases.

Prof. Bragg* has compared the ionisations along the course of an α -particle in some gases and found them approximately similar, and this is therefore probably true in general. Thus the relative ionisations in various gases for the same velocity of the α -particle are independent of the magnitude of the velocity of the α -particle.

Therefore, if T and I denote respectively the total ionisation and ionisation per cubic centimetre of a gas in terms of air as the standard, and S denotes the stopping power of a molecule of the gas in terms of that of an air molecule, then $1/S$ is the range of an α -particle in the gas in terms of its range in air, and the relation between the qualities T , I , and S is given by

$$ST = I. \quad (1)$$

Let us assume that it requires the same amount of energy to make an ion from an atom, whether it is free or combined with other atoms. Let T_a denote the total number of ions that would be made by an α -particle in a gas whose molecules consist of atoms a , and T_b the total number that would be made in a gas whose molecules consist of atoms b , so that, if the energy of the α -particle is denoted by unity, the respective energies required to make an ion from each of the atoms a and b are $1/T_a$ and $1/T_b$. Let S_a and S_b respectively denote the stopping powers of the atoms a and b in terms of that of an air molecule. Then, if we have a gas whose molecules consist of N_a atoms a combined with N_b atoms b , the stopping power of this gas will be $N_a S_a + N_b S_b$, and the range of an α -particle in terms of its range in air at the same pressure will be $1/(N_a S_a + N_b S_b)$.

The average amount of energy expended by the α -particle along a length of path in the gas equal to the complete range of the α -particle in air is, therefore, $N_a S_a + N_b S_b$, and therefore the respective amounts of energy expended on the atoms a and b are $N_a S_a$ and $N_b S_b$. The respective amounts of energy expended along the whole path of the α -particle on the atoms a and b are therefore $\frac{N_a S_a}{N_a S_a + N_b S_b}$ and $\frac{N_b S_b}{N_a S_a + N_b S_b}$.

The total ionisation, T_{ab} , of the α -particle in the gas is, therefore, given by

$$T_{ab} = \frac{N_a S_a}{N_a S_a + N_b S_b} \left/ \frac{1}{T_a} \right. + \frac{N_b S_b}{N_a S_a + N_b S_b} \left/ \frac{1}{T_b} \right.,$$

that is by

$$T_{ab} = \frac{T_a N_a S_a + T_b N_b S_b}{N_a S_a + N_b S_b}. \quad (2)$$

* 'Trans. Roy. Soc. of South Australia,' Oct., 1906.

Writing this value of T_{ab} for T in equation (1) and $N_a S_a + N_b S_b$ for S , we get

$$I_{ab} = T_a N_a S_a + T_b N_b S_b. \quad (3)$$

From the manner in which equations (2) and (3) were obtained, it will be readily seen that, in general, if the molecules of a gas consist of atoms a, b, c, \dots

$$T_{abc\dots} = \frac{T_a N_a S_a + T_b N_b S_b + T_c N_c S_c + \dots}{N_a S_a + N_b S_b + N_c S_c \dots} \quad (4)$$

and

$$I_{abc\dots} = T_a N_a S_a + T_b N_b S_b + T_c N_c S_c + \dots \quad (5)$$

Now, $T_a S_a$ is the ionisation per cubic centimetre in a gas whose molecules consist of atoms a , in terms of air as the standard, and $T_b S_b$ the ionisation per cubic centimetre in a gas whose molecules consist of atoms b , etc. (See equation (1).)

Therefore, if the assumption made in the beginning is true, the ionisation in a complex gas must be an additive property of the constituent atoms.

The ionisation values of a number of gases are given in the fifth column of Table I. A large number of these are taken from a paper by Prof. Bragg.[†]

Table I.

	Atomic ionisation per c.c.	Atomic total ionisation.	Gas.	Experimental ionisation per c.c.	Calculated ionisation per c.c.	Experimental total ionisation.	Calculated total ionisation.	Calculated density of gases.
H	0·175	1·33	Air	1·00	1·00	1·00	1·00	1·00
C	0·51	1·12	O ₂	1·15	1·10	1·09	1·04	1·11
N	0·47	0·952	CO ₂	1·59	1·61	1·08	1·09	1·53
O	0·55	1·04	CH ₄ O	1·74	1·76	1·22	1·23	1·11
S	1·24	1·66	C ₂ H ₂	1·40	1·37	1·26	1·26	0·903
Cl	1·16	1·48	C ₂ H ₄	1·73	1·72	1·28	1·28	0·972
Br	1·72	1·46	C ₂ H ₆ O	2·46	2·62	1·23	1·31	1·60
I	2·26	1·52	C ₄ H ₁₀ O	4·40	4·34	1·32	1·30	2·57
			C ₆ H ₆	4·30	4·11	1·29	1·23	2·71
			C ₆ H ₁₂	4·85	4·65	1·35	1·30	2·50
			C ₂ H ₄ O	2·14	2·27	1·17	1·24	1·53
			N ₂ O	1·53	1·49	1·05	1·02	1·53
			C ₂ N ₂	1·94	1·96	—	—	1·81
			CH ₃ I	3·43	3·29	1·33	1·28	4·93
			C ₂ H ₅ I	4·00	4·15	1·28	1·33	5·42
			CHCl ₃	4·08	4·16	1·29	1·32	4·15
			C ₂ H ₅ Cl	3·12	3·05	1·32	1·29	2·24
			CCl ₄	5·28	5·15	1·32	1·29	5·35
			CS ₂	2·99	2·99	1·37	1·37	2·64
			CH ₃ Br	2·75	2·75	1·32	1·32	3·30
			SO ₂	2·01	2·34	—	—	2·22
			NH ₃	0·81	0·99	—	—	0·590
			H ₂	0·24	0·35	—	—	0·0694
			H ₂ †	0·226				
H	0·132	0·754						
C	0·456	0·894						
N	0·493	1·05						
O	0·530	0·962						
S	0·745	0·603						
Cl	0·785	0·676						
Br	1·18	0·685						
I	1·48	0·658						
H*	—	1·10						

† 'Trans. Roy. Soc. of South Australia,' Oct., 1906.

who obtained them by measuring the ionisation of a certain point along the course of a bundle of α -rays. The value for NH_3 was obtained by multiplying the total number of ions made in NH_3 , as found by Laby,* by the calculated stopping power (equation (1)), while the others, with the exception of C_2N_2 , were obtained by the writer, using the same method as Prof. Bragg. The value for C_2N_2 is taken from Strutt's paper, and I have also placed his value for H_2 under H_2^\dagger in the table. The method used by Strutt is not altogether unobjectionable in the light of more recent knowledge of the properties of the α -particle, unless special precautions are taken, but still his values, with the exception of CHCl_3 , agree fairly well with those obtained by Prof. Bragg for the same gases.

The ionisation is approximately an additive quantity. If the atomic ionisation values given in the second column of the table are used to calculate the ionisations of the various gases, the values given in the sixth column are obtained. The agreement between the experimental and calculated values, omitting SO_2 , NH_3 , and H_2 for the present, is as good as can be expected.

This shows then, that the assumption made in the beginning is so far true, and that, therefore, the amount of energy necessary to make an ion from an atom of these gases is independent of chemical combination. It should be observed that from the existence of an additive ionisation law alone it does not follow that the energy spent to make an ion from an atom is independent of chemical combination. For the total number of ions made by an ionising agent, when its energy decreases from e_1 to e_2 , depends, besides the intensity of ionisation along its course, on the distance traversed during this change of energy.

If we divide the atomic ionisation of an atom a , that is, $T_a S_a$, by the stopping power of the atom in terms of that of an air molecule, we get T_a , the atomic total ionisation (see equation (5)), and the reciprocal of this gives the energy necessary to make an ion from an atom a in terms of an atom of an air molecule as the standard. The stopping powers of the atoms occurring in the gases given in Table I have been calculated by the square root law from the atomic weights, taking the atomic weight of the standard air atom as 14.4, and are given in the lower part of the second column. The atomic total ionisation and energy necessary to make an ion from an atom, calculated from the second column, are given in the third column.

It will be seen that the α -particle spends the least amount of energy per ion when sulphur atoms are ionised, and the greatest amount when nitrogen atoms are ionised. The expenditure of energy by the α -particle on atoms of

* 'Pass. of Electr. through Gases,' by Prof. J. J. Thomson, new edition, p. 369.

the same kind in a gas consists in ionisation, collision, etc., the sum total of the energy expended being proportional to the square root of the atomic weight of an atom. It does not follow, therefore, that the α -particle finds it really easier to ionise a sulphur atom than a nitrogen atom; all we can say is that the total expenditure of energy per ion is less with the sulphur atom.

The gases NH_3 , H_2 , SO_2 , especially H_2 , show deviations from the additive law, the calculated being greater than the experimental values, and I have not tried to bring them into a line with the other gases, because these gases show similar deviations with other ionising agents. Thus the chemical bond affects the ionisation per cubic centimetre in these gases. If the stopping powers of these gases follow the square root law, the energy spent on any one of their atoms is the same as when it occurs in any of the other gases. The stopping power of H_2 has been determined and was found to be normal,* and therefore the α -particle spends more energy per ion when made from a hydrogen atom of a molecule of H_2 than from a hydrogen atom of a molecule of any of the other gases. Thus the chemical bond affects not alone the ionisation per cubic centimetre in H_2 , but also the energy spent per ion, and this is probably also true for NH_3 and SO_2 . The energy spent per ion of a H atom, when it occurs in H_2 , is given under H^* in Table I.

In the seventh column of Table I, the experimental values of the total ionisation are given for some of the gases. The greater number of these are taken from Professor Bragg's paper. The equations (4) and (5) may be used to calculate the total ionisation and the ionisation per cubic centimetre of a gas obeying the additive ionisation law and the square root law for the stopping power. The total ionisation values calculated by equation (4) are given in the eighth column of the table. For the denominator of the fraction in equation (4), which is the stopping power of the gas, I have used the experimental value of the stopping power† instead of calculating it from the atomic stopping powers given in the second column, because this gives a better agreement between the calculated and experimental total ionisation.

It may be mentioned that Prof. Bragg has shown‡ that the ionisation per cubic centimetre in a gas, denoted by ks in his paper, is approximately proportional to the molecular volume of a molecule. The experiments on the ionisation of various gases by γ -rays will now be described.

* Bragg and Kleeman, 'Phil. Mag.', Sept., 1905.

† Bragg and Kleeman, 'Phil. Mag.', Sept., 1905, and Bragg, 'Trans. Roy. Soc. of South Australia,' vol. 30, p. 1.

‡ *Loc. cit.*

§ 2. Fig. 1 is a sketch of the apparatus and their arrangement in these experiments. A is the ionisation chamber, the outside case of which was connected to a potential of 200 volts. It was of a cylindrical form and had a height and diameter of 10 and 9 cm. respectively. The electrode B was connected to an electrometer of the Dolezalek type. The source of γ -rays was a quantity of radium placed at such a distance from the chamber that a convenient leak was obtained, which used to be about 200 mm. divisions in ten seconds. The process of filling the ionisation chamber with pure vapour of some liquid was as follows:—The stop-cock *a* was opened and *b* closed, and the chamber, together with the glass flask C, exhausted by means of

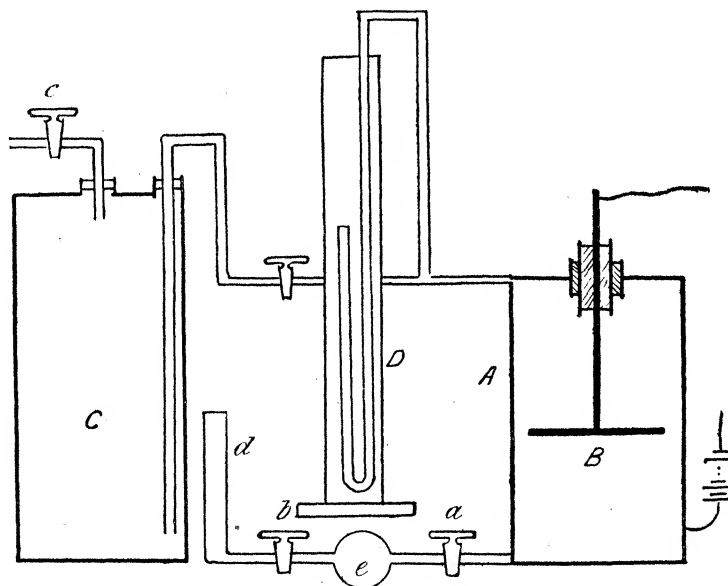


FIG. 1.

a Fleuss pump till the pressure, indicated by the mercury gauge D, was a few millimetres, when the stop-cock *c* was closed. Some of the liquid was then poured into *d*, and by opening the stop-cock *b* part of the liquid was allowed to run into the catch *e*, and evaporation allowed to go on till the desired vapour-pressure was reached, when the stop-cock *a* was closed. Care was taken that the pressure of each vapour was not too near that necessary to produce condensation. The air which was not removed from the ionisation chamber by the pump was swept by the stream of vapour into the flask C, whose capacity was about ten times that of the ionisation chamber. When the standard air leak was taken, the pressure was always so arranged that the leak was about equal to that of the vapour, in order to avoid the error introduced by the change of capacity of electrometer with the deflection.

The first and second swing of the electrometer needle, when the current was broken, were usually read, and the position of rest of the needle calculated by the formula given in a paper* by the writer.

With some of the vapours (CS_2 , CCl_4 , etc.) the pressure in the ionisation chamber gradually decreased, but ultimately reached a steady state. This was probably due to some chemical action between the vapour and the rubber washers and tubing and the brass case. The leak also as a rule decreased, although corrected for the decrease of pressure, and ultimately reached a steady state. In order to avoid this disturbing effect, the ionisation chamber was first filled with vapour at a lower pressure than that at which the ultimate readings were taken, and allowed to stand for one or two minutes. The vapour was then swept into the vessel C by fresh vapour, and the readings rapidly taken. In this manner very consistent readings were obtained. But the ionisation values obtained for some of the vapours were considerably greater than those obtained by Strutt. The reason for this probably is that Strutt used a very weak source of γ -rays, and therefore had to extend a single reading over a considerable time, during which the vapour may have become more or less impure. It is also of importance to secure pure chemicals; the writer used Kahlbaum's.

The ionisation values of a number of gases, in terms of air at the same pressure as the standard, are given in the eighth column of Table II. Each value, with a few exceptions, is the mean of three separate determinations given in the preceding three columns. The ionisation current was smaller with each vapour than that obtained with air at a pressure of 75.23 cm. of mercury, and when leaks were taken with air for the pressures 75.23, 53.63, 34.94, 14.10 cm., and reduced to correspond to the pressure 75.23 cm., the numbers 2003, 2018, 2009, 2060, were obtained, which show that the ionisation was proportional to the pressure, in this case with air and, therefore, also for the gases.

The ionisation of a gas by γ -rays is an additive property of the atom. The ninth column of the table contains the ionisation values calculated from the atomic ionisations given in the second column. The agreement between the experimental and calculated values is very good, with the exception of H_2 , SO_2 , NH_3 , the calculated values being in their case, as with the α -rays, greater than those given by experiment. Strutt's value for H_2 , given in the table under H_2^\dagger , agrees fairly well with my own. Thus the chemical bond in these gases diminishes the ionisation by γ -rays also. The atomic ionisations are roughly given by the equation

$$I = 0.11 + 0.035 \times w, \quad (6)$$

* 'Phil. Mag.', p. 276, Oct., 1906.

where w denotes the atomic weight. The ionisations in the third column of the table are calculated from this equation.

Table II.

	Atomic ionisation.	Ionisation from equation (6).	Gas.				Ionisation per c.c.	Calculated ionisation per c.c.	Calculated density of gases.
H	0.18	0.145	Air	—	—	—	1.00	1.00	1.00
C	0.46	0.53	O ₂	—	—	1.16	1.16	1.16	1.11
N	0.45	0.60	CO ₂	—	—	1.58	1.58	1.62	1.53
O	0.58	0.67	C ₂ H ₄ O	2.15	2.17	2.19	2.17	2.22	1.53
S	1.60	1.23	C ₅ H ₁₂	4.45	4.53	4.61	4.53	4.46	2.50
Cl	1.44	1.33	CH ₄ O	1.74	1.79	1.73	1.75	1.76	1.11
Ni	1.82	2.07	C ₄ H ₁₀ O	4.33	4.18	4.36	4.29	4.22	2.57
Br	2.81	2.91	C ₆ H ₆	3.93	3.94	3.95	3.94	3.84	2.71
I	4.50	4.57	C ₂ N ₂	—	—	—	1.71	1.82	1.81
			N ₂ O	—	1.54	1.55	1.55	1.48	1.53
			C ₂ H ₅ Cl	3.18	3.21	3.19	3.19	3.26	2.24
			CHCl ₃	4.92	4.90	4.97	4.93	4.96	4.15
			CCl ₄	6.37	6.38	6.25	6.33	6.22	5.35
			CS ₂	3.64	3.68	3.66	3.66	3.66	2.64
			CH ₃ Br	3.73	3.82	3.88	3.81	3.81	3.30
			C ₂ H ₅ Br	4.66	4.66	4.58	4.63	4.63	3.78
			CH ₃ I	5.35	5.41	5.32	5.37	5.50	4.93
			C ₂ H ₅ I	6.56	6.37	6.47	6.47	6.32	5.42
			Ni(CO) ₄	—	—	5.98	5.98	5.98	5.94
			NH ₃	0.894	0.898	0.903	0.898	0.99	0.590
			SO ₂	2.29	2.26	2.25	2.27	2.76	2.22
			H ₂	—	—	0.160	0.160	0.36	0.0694
			H ₂ †	—	—	—	0.169	—	—
H	5.18	0.193							
C	1.10	0.909							
N	0.926	1.08							
O	1.04	0.962							
S	1.44	0.694							
Cl	1.17	0.855							
Ni	0.888	1.13							
Br	1.01	0.090							
I	1.02	0.980							
H*	—	0.434							

Experiments on the absorption of γ -rays by various substances show that if the rays are homogeneous the absorption takes place according to an exponential law, the absorption coefficient being proportional to the density of the absorbing substance. If the absorbing substances were distributed in space so that there are always the same number of molecules per cubic centimetre, as is the case with gases at the same pressure, then the absorption coefficient would be proportional to the sum of the weights of the atoms of a molecule, and therefore an additive quantity.

Let us suppose that the γ -rays do not spread out along their course. Let T denote the total ionisation in a cylinder of gas of 1 cm. cross-section and infinite length in terms of the total ionisation in a similar cylinder of air, the axes of the cylinders being parallel to the direction of the rays. Let λ denote the absorption coefficient, and I the ionisation per cubic centimetre

where the rays enter* the cylinder, in terms of air at the same pressure as the standard. Then

$$T = I \int_0^{\infty} e^{-\lambda x} . dx,$$

and therefore

$$T = I\lambda. \quad (7)$$

We have thus a similar equation connecting the total ionisation, the absorption and the ionisation per cubic centimetre, in the case of γ -rays to that which obtains in the case of α -rays. Since λ can be calculated, being in a given case equal to the molecular weight of the gas divided by that of air, and I calculated by means of the atomic ionisations given in the second column of Table II, we can obtain from equation (7) the total ionisation by γ -rays in a given gas, a quantity that will scarcely be ever determined directly, but only by some indirect method such as this. The calculated total ionisation values for a number of gases are given in the second column of Table III, and in the third column the experimental values of the total ionisation by the α -particle are placed for comparison. It will be seen that the values, like those of the α -particle, all lie between the numbers one and two.

Table III.

Gas.	Calculated total γ -ionisation.	Experimental total α -ionisation.
Air	1·00	1·00
O ₂	1·04	1·09
CO ₂	1·03	1·08
C ₂ H ₄ O	1·42	1·17
C ₃ H ₁₂	1·81	1·35
CH ₄ O	1·56	1·22
C ₄ H ₁₀ O	1·67	1·32
C ₆ H ₆	1·45	1·29
N ₂ O	1·01	1·05
C ₂ H ₃ Cl	1·42	1·32
CHCl ₃	1·19	1·29
CCl ₄	1·18	1·32
CS ₂	1·39	1·37
CH ₃ Br	1·16	1·32
CH ₃ I	1·09	1·33
C ₂ H ₅ I	1·19	1·28

We can deduce from equation (7) two equations similar to the equations (4) and (5) relating to the α -particle. When the energy of an α -particle decreases from e_1 to e_2 in a gas, the distance traversed is equal to the reciprocal of the sum of the square roots of the weights of the atoms of a molecule multiplied by a constant, this constant being the same from gas to gas if they are at the same pressure. In the case of γ -rays, the distance

traversed during which their energy decreases from e_1 to e_2 is given by $e_1 e^{-\lambda x} = e_2$, that is by $x = \frac{1}{\lambda} \log \left(\frac{e_1}{e_2} \right)$. Since $\log (e_1/e_2)$ is constant, the distance traversed in a gas is inversely proportional to the sum of the atomic weights of a molecule. Thus λ may be called the stopping power of a gas with respect to γ -rays. Therefore, if we introduce the quantities atomic ionisation and atomic total ionisation, and assume that the amount of energy spent by the γ -rays to make an ion from an atom is independent of chemical combination, we can, as is obvious, deduce two similar equations as (4) and (5) for the γ -rays. Thus we see that, if the ionisation by γ -rays follows an additive law for some gases, then the above assumption, that the energy spent per ion per atom is independent of chemical combination, is true for these gases.

The total atomic ionisation and the energy spent per ion per atom, obtained in a similar way to the same quantities for the α -particle, are given in the lower parts of the second and third columns of Table II. It will be seen that in the case of the atoms given in the table, the γ -rays spend the least amount of energy per ion when ionising hydrogen atoms and the greatest amount when ionising nickel atoms, nitrogen atoms coming next. The α -particle, it will be remembered, spends the least amount of energy per ion when ionising sulphur atoms. As pointed out in the case of the α -particle, it does not follow that the ionisation must necessarily account for all the energy expended. If each of the coefficients of absorption of the gases SO_2 , NH_3 , H_2 is proportional to the sum of the weights of the atoms of a molecule, as it has been taken to be in the case of the other gases, then the γ -rays spend more energy per ion made from an atom when it occurs in these gases than when it occurs in any of the others. Assuming the absorption coefficient of H_2 to be normal, the energy spent per ion of an atom of H when it occurs in H_2 is given under H^* in the table.

The experiments on ionisation by γ -rays are complicated by the fact that the walls of the ionisation vessel give off secondary cathode rays which possess ionising power themselves. It will be seen afterwards that the β -ray ionisation is almost exactly the same as that obtained for the γ -rays, therefore, if the ionisation by these secondary rays were of some magnitude, and the γ -ionisation values were different from the β , this would not be the case. Thus we conclude that, whether the ionisation was appreciably affected by these secondary rays or not, the numbers in the table represent the γ -ionisation in the various gases. We will now describe the experiments made with β -rays.

§ 3. The apparatus used and their arrangement in the experiments with the

β -rays are shown in fig. 2. H is the ionisation chamber. A flat circular dish *k* of diameter 10.5 cm., and having a small hole in the bottom, contained uranium oxide, which was moistened when put into the dish and then allowed to dry, becoming a solid cake. The dish, in order to cut off the α -particles, was covered with aluminium foil bent down at the side, and held

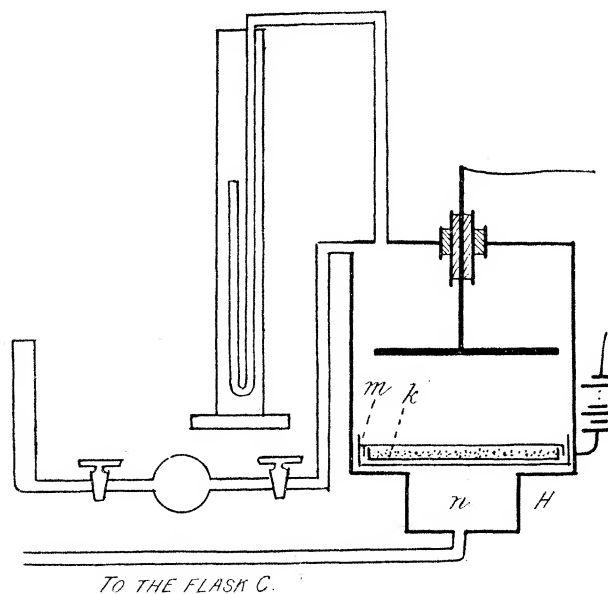


FIG. 2.

down by brass cross-pieces soldered to a similar but larger dish *m*, into which *k* was placed. The distance of the aluminium foil from the electrode was 5 cm. It will be seen from the diagram that the motion of the air or vapour, during exhaustion or the letting in of vapour, was always such that if any uranium particles were carried along by the current of gas, they would be swept into the compartment *n*, and thus would not affect the β -leak. The leak, when the chamber was full of air at atmospheric pressure, was about 63 mm. divisions of the scale in 10 seconds.

The β -ionisation values of the gases in Table II are given in the sixth column of Table IV. Leaks were taken with air for the pressures 15.82, 35.57, 56.12, 77.57 cm. of mercury and reduced to a pressure of 77.57 cm., and the numbers 2430, 2396, 2340, 2400 obtained, which show that the ionisation was proportional to the pressure. The leaks with the gases in the table were generally smaller than that of air at atmospheric pressure, and therefore the ionisation must have been approximately proportional to the pressure in the neighbourhood of the pressures used.

Table IV.

	Atomic ionisation.	Gas.			Ionisation per c.c.	Ionisation per c.c., γ -rays.	Calculated ionisation per c.c.	Calculated density of gases.
H	0.18	Air	—	—	1.00	1.00	1.00	1.00
C	0.46	O ₂	1.16	1.19	1.17	1.16	1.16	1.11
N	0.475	CO ₂	1.62	1.58	1.60	1.58	1.62	1.53
O	0.58	C ₂ H ₂ O	2.10	2.14	2.12	2.17	2.22	1.53
S	1.60	C ₂ H ₁₂	4.50	4.61	4.55	4.53	4.46	2.50
Cl	1.44	CH ₃ O	1.67	1.71	1.69	1.75	1.76	1.11
Br	2.67	C ₄ H ₁₀ O	4.44	4.35	4.39	4.29	4.22	2.57
I	4.10	C ₆ H ₆	3.92	3.98	3.95	3.94	3.84	2.71
		C ₂ N ₂	—	—	1.86	1.71	1.87	1.81
		N ₂ O	1.55	1.56	1.55	1.55	1.53	1.53
		C ₂ H ₅ Cl	3.19	3.30	3.24	3.19	3.26	2.24
		CHCl ₃	4.88	5.00	4.94	4.93	4.96	4.15
		CCl ₄	6.23	6.33	6.28	6.33	6.22	5.35
		CS ₂	3.58	3.65	3.62	3.66	3.66	2.64
		CH ₃ Br	3.70	3.77	3.73	3.81	3.67	3.30
		C ₂ H ₅ Br	4.41	4.40	4.41	4.63	4.49	3.78
		CH ₃ I	5.11	5.11	5.11	5.37	5.10	4.93
		C ₂ H ₅ I	—	5.90	5.90	6.47	5.92	5.42
		NH ₃	0.885	0.892	0.888	0.898	1.02	0.590
		SO ₂	2.25	2.26	2.25	2.27	2.76	2.22
		H ₂	—	0.165	0.165	0.160	0.36	0.0694
		H ₂ *	—	—	0.157	0.169		

The ionisation values obtained with γ -rays are placed in the seventh column for comparison. It will be seen that they are almost exactly the same as those obtained with β -rays, the only appreciable difference occurring with the iodides. The eighth column contains the ionisation values calculated from the atomic ionisations given in second column, the atomic ionisations being the same as those used in the case of γ -rays, except for the atoms N, Br, and I, but the atomic ionisations of I only differ appreciably from one another.

An interesting deduction can be made from the additive ionisation law. Since the ionisation is independent of chemical combination, the number of electrons lost by an atom is a constant which is independent of chemical combination, but which may vary with the kind of atom. Now, Townsend's diffusion experiments, as well as the experiments by Prof. Thomson on the charge of an ion, show that the positive and negative ions have equal charges when made by β -, γ -, or X-rays, in air, CO₂, or O₂. Thus the atoms N, O, C lose one electron only when ionised by one of these ionising agents, and not more than one atom of a molecule gets ionised. Therefore, as an example, with CO₂, the ratio of the number of oxygen atoms per cubic centimetre, or molecules in which the oxygen atom is ionised, to the number

of molecules in which the carbon atom is ionised is, in the case of γ - or β -rays, as 2×0.58 to 0.46 , that is, as 1.16 to 0.46 . That the ionised atom loses one electron only is probably true for all kinds of atoms. In the case of the α -particle, there is scarcely any evidence as to the number of electrons lost by an ionised atom. The velocities of the positive and negative ions under an electric force, and other properties, suggest, however, that an atom loses one electron only.

The atomic ionisation for α -, β -, and γ -rays has been plotted against the atomic weight in fig. 3. There is an interesting similarity between the



FIG. 3.

curves obtained, shown by two sets of kinks. The curves have been separated somewhat, to prevent overlapping. The ionisation with each ionising agent thus seems to be some periodic function of the atomic weight. The first short period of the periodic classification of the elements is represented by H, C, N, O, the second short period by S, Cl, and the first and second long period by Ni, Br, and I respectively. The similarity between these curves means that similar conditions regulate the chance of a number of atoms getting ionised by one of these ionising agents. And this may be so if the electron is pulled or knocked out of an atom in one case, while an absorption of energy till something like an explosion of the atom occurs takes place in another case; for, if one gas is more easily ionised than another by the first

process, we should also expect that a smaller amount of energy would be necessary to produce an explosion of an atom of that gas.

The curves D and E in fig. 3 show the relation between the energy spent per ion and the atomic weight for α - and γ -rays. These curves also resemble one another, which means that similar conditions regulate the total expenditure of energy per ion. It should be observed that from the way the energy spent per ion is obtained, it does not follow that if the curves A and C resemble one another, D and E must resemble one another. The numbers representing the energy spent per ion are only relative and, in the case of the α -particle, the absolute amount of energy spent per ion decreases as the α -particle approaches the end of its course. This follows from the fact that the α -particle makes more ions towards the end of its course, while the rate of expenditure of energy all along the course is the same. It appears from the curves D and E and, in the case of the α -particle, also from the foregoing fact, that the energy spent per ion is not connected in a simple way with the atomic weight and, therefore, not connected in a simple way with the absorption of energy. The abnormal behaviour of H_2 with respect to the energy spent per ion per atom and the ionisation per cubic centimetre, in comparison with other gases, is interesting in connection with the abnormal scattering of cathode rays in H_2 , which is pointed out and discussed by Professor Thomson.*

We have no experimental evidence on the connection of the atomic or molecular weight of a gas with the distance traversed by a β -ray while its energy decreases from e_1 to e_2 , say; and therefore we are not able to determine in this case the relative amounts of energy spent per ion per atom, and whether the amount of energy spent per ion is independent of chemical combination.

Strutt showed in his paper that the ionisations by α -, β -, and γ -rays, of the gases examined by him, were nearly proportional to the densities of the gases. But this is accidental; moreover, only a rough approximation to the density is shown by the ionisation values given in this paper, and the law does not hold at all for many of the other gases. This will be evident from comparing the ionisations with the densities of the gases given in the last column of each table.

I have much pleasure in thanking Professor Thomson for his kind interest and ready advice at all times.

* 'The Discharge of Electricity through Gases,' p. 332.